Summertime Storm Initiation and Evolution in Central Arizona

A Dissertation Prospectus

by

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Abstract

High resolution radar reflectivity data, coupled with digital elevation terrain information, is examined to determine the important meteorological and geographical attributes that lead to preferred areas for convective initiation and propagation in central Arizona. Previous studies show that terrain influences the climatological diurnal precipitation cycle in central Arizona during the summertime, however, a study examining the role of terrain and associated synoptic and mesoscale conditions on preferred storm initiation locations and storm evolution does not exist. To this end, WSR-88D 1-km resolution radar reflectivity mosaics, digital elevation data, and surface and upper-air data are used to examine important meteorological traits that lead to preferred areas for storm occurrence over central Arizona during three summer seasons.

Preliminary analyses of 1999 radar reflectivity mosaics indicate four reflectivity regimes, including: 1) the eastern mountain regime, 2) the central and eastern mountain regime, 3) the central, eastern, and Phoenix regime, and 4) the widespread regime. These reflectivity regimes are named to reflect the importance of elevated terrain in the initiation and evolution of storms in central Arizona. Analyses of associated synoptic-scale conditions at Phoenix, such as tropospheric moisture and wind, suggest that the depth of low-level moisture and the direction of steering level winds at Phoenix may be related to the reflectivity regime that occurs on a given day. Future work will examine the sensitivity of storm initiation locations and evolution, over three summer seasons, to both synoptic-scale and mesoscale conditions over central Arizona.

1. Introduction

During the summertime, a daily forecast challenge in central Arizona is the potential for convective storm development over Phoenix and its surrounding suburbs, where the largest segment of the state's population resides. Precipitation forecasts are important for central Arizona because summertime storms often create transportation problems over local washes, damaging winds at the surface, reduced visibility due to blowing dust, and copious lightning (Hales 1975; Schmidli 1986; Smith and Gall 1989). Since diurnal temperature cycles are moderated by precipitation occurrence and cloudiness, improved forecasts of precipitation probability may, in turn, help improve diurnal temperature forecasts. Consequently, more reliable precipitation probability forecasts may improve both public and forecaster confidence in precipitation and temperature forecasts, as well as National Weather Service (NWS) verification statistics.

In addition to creating weather hazards, summertime storms provide rainfall that is important to Arizona's economy. For example, farmers depend on the 15% of annual runoff received during the summertime to keep their businesses and crops thriving (Jurwitz 1953; Sellers and Hill 1974; Ester 2001, personal communication). Similarly, cattle ranchers in Arizona depend on summertime rainfall to sustain the growth of grass for their cattle. Rainfall is indirectly important to power companies who may buy or sell power depending on available temperature forecasts. Thus, more reliable forecasts of precipitation probability can provide information that is vital for decision-making by such weather-sensitive businesses.

Forecasts of summertime precipitation probability are challenging in central Arizona owing to interactions between a variety of forcing mechanisms that work in conjunction with sufficient moisture and instability to produce storms. To a large extent, this forecast challenge arises from the complex terrain surrounding the Sonoran Desert, which includes the Central mountain ranges and the Mogollon Rim to the north, and the Southeast Highlands to the east and southeast (Fig. 1). Even though such elevated terrain features surround Phoenix to the north and east, interactions between synoptic regimes and elevated terrain features remain largely unexamined. Understanding the ingredients conducive to precipitation over central Arizona is also challenging because summertime large-scale dynamics are weak compared to wintertime large-scale dynamics (Adams and Comrie 1997) and operational mesoscale forecasts tend to be poor (Dunn and Horel 1994a,b).

Scientific understanding of the mechanisms responsible for summertime weather events in Arizona arises mostly from climatological studies, including studies of seasonal changes in circulation patterns over North America (Adams and Comrie 1997), diurnal precipitation patterns over Arizona (Balling and Brazil 1987; King and Balling 1994; Watson et al. 1994b; MacKeen and Zhang 2000), and synoptic patterns associated with intraseasonal variations in precipitation (Carleton 1986; Watson et al. 1994a; Mullen et al. 1998). While such studies highlight general tendencies for seasonal circulation changes, diurnal storm development, and synoptic patterns associated with relatively dry vs. relatively wet periods, they have done little to advance our understanding of the mechanisms that influence where storms are most likely to develop and how they may evolve on a given day. This lack of advancement in our understanding of mechanisms important to forecasting storm development over central Arizona is likely due to our limited understanding of the mesoscale processes at work. The study of mesoscale processes important to convective storm development in central Arizona is limited in scope due to a lack of operational mesoscale data sets. However, the installment of high-resolution Weather Surveillance Radar-1988 Dopplers (WSR-88D) in Phoenix (1994) and Flagstaff (1996), coupled with the creation of the Mesowest network (Horel et al. 2002) across central Arizona and a new rawinsonde site in Phoenix, provides the opportunity to investigate some of the mesoscale processes which may be important to forecasting where storms are expected to initiate and evolve on a given day.

The main goal of this study is to advance our understanding of the mesoscale processes that influence where storms initiate and how they evolve over the mountainous and desert terrain of central Arizona. This goal is addressed by using the above data sets to answer three related questions. The first question is, “Do storms tend to initiate and evolve repeatedly over similar areas?” This question is important because the presence or lack of repeated storm regimes may indicate the relative importance synoptic-scale conditions in the development of storms in central Arizona. Hence, the second question addressed is, “How are synoptic-scale conditions related to storm initiation and evolution?” This question addresses the relative importance of interactions between elevated terrain features and synoptic-scale conditions toward storm development. The third question is, “What mesoscale processes are related to storm development over Phoenix?” As mentioned previously, this third question of particular importance because it is likely that a better understanding of mesoscale processes in central Arizona is necessary to provide improved forecasts of precipitation and hazardous weather to the growing population in Phoenix and surrounding suburbs.

In Chapter 2, mechanisms associated with the development of Arizona’s summertime wet season are reviewed. Chapters 3 and 4 describe the data and methodology, respectively. Preliminary results for the relation of synoptic regime to repeated storm initiation locations and evolutions are presented in chapter 5. Future research directions for this dissertation are discussed in chapter 6.

Chapter 2: Background

On average, Arizona's summertime wet season occurs from July through mid-September, and produces between 40–60% of the state's annual rainfall (Jurwitz 1953; Sellers and Hill 1974). The duration of Arizona's summertime wet season coincides with seasonal reversals in tropospheric wind direction, which, by definition, is a monsoon. Herein, this monsoon is called the North American monsoon (NAM). Seasonal changes in circulation which comprise the NAM extend from western Mexico through the southwest U.S. (Fig. 2), and correspond with a shift from hot, dry weather to hot, humid weather and increased convective storm occurrence over western Mexico, New Mexico and Arizona (e.g., Campbell 1906; Beals 1922; Blake 1923; Bryson and Lowry 1955; Tang and Reiter 1984; Douglas et al. 1993; Adams and Comrie 1997). Such summertime rainfall occurs in the form of thunderstorms and mesoscale convective systems (Sellers and Hill1974; Hales 1975; Schmidli 1986; Smith and Gall 1989). The circulations comprising the NAM, and associated mechanisms that support the summertime precipitation maximum over central Arizona, are described below.

a. The NAM

The NAM is defined by reversals in wind direction between low–mid levels that occur in response to interactions between the underlying topography and incoming solar radiation (Tang and Reiter 1984). Owing to solar heating over the deserts of Arizona, southeastern California, and northwestern Mexico, the wintertime surface high is replaced by a thermal low, which results in a low-level (500 m–850 mb) change in wind direction over Arizona from westerly to southerly (Tang and Reiter 1984; Rowson and Colucci 1992; Douglas et al. 1993; Adams and Comrie 1997; Tucker 1999). The spin-up of this thermal low is accompanied by the northward retreat of the westerlies and the development of a mid–upper level high pressure system over the southwest U.S.. Like the thermal low, this mid–upper level high pressure system produces a change in mean wind direction over Arizona from westerly to southerly (Fig. 3; Reed 1933,1939; Bryson and Lowry 1955; Douglas et al. 1993; Adams and Comrie 1997).

The correspondence of the NAM to summertime precipitation occurrence over western Mexico, Arizona, and New Mexico is recognized in the early 1920s, when summertime storm occurrence is related to both the development of the thermal low (Campbell 1906; Beals 1922; Blake 1923) and the transport of moisture from the Gulf of California into the southwest U.S. (Blake 1923). More concrete evidence for such low-level transport arises when the Gulf of California is identified as a source of low-level moisture flux for southern Arizona during the summer season (Rasmussen 1967). Soon afterward, Hales (1972, 1974) and Brenner (1974) show that the transport of moisture from the Gulf of California into the southwest U.S. sometimes occurs as intermittent “surges” of low-level moisture. Surges approaching southern Arizona are characterized by relatively strong low-level southerly winds (10–15 m s^{-1}), cool temperatures, high pressure, high dewpoints, and low–mid level cloudiness (Hales 1972a, 1974; Brenner 1974; Stensrud et al. 1997). Hales (1972) speculates that such low-level moisture is “channelled” northward—between the Sierra San Pedro Martir of Baja, California, and the Sierra Madre Occidental of Mexico—from the Gulf of California into southern Arizona via a meridional pressure gradient force. According to Hales (1974), surges are associated with an enhancement of the meridional temperature and pressure gradients that normally exist between the relatively cool air and high pressure at the southern Gulf of

California and the relatively hot desert air associated with the southwest U.S. thermal low (Figs. 6, 7 of Hales 1974). Hale's (1972, 1974) argument that an enhanced pressure gradient force is responsible for surges is based on the results from a linear correlation coefficient analysis between five-day running means of 850-mb relative humidity at Tucson and 850-mb termperature (^{o}C) at Empalme. Hale's analyses (1974) show that, at zero, 24- and 48- hour time lags, the associated correlation coefficients are high: -.71, -.76, and -.69, respectively. Hales (1972, 1974) credits the relatively cool air at Empalme, and therefore an increased pressure gradient between Empalme and Tucson, to influxes of tropical air from tropical disturbances that exist intermittently over the southern part of the Gulf of California (Fig. 4). The importance of tropical disturbances as catalysts for surges is supported by Brenner (1974). Based on a case study, Brenner (1974) shows that following the passage of an easterly wave, an area of convective precipitation forms over the southern Gulf of California. This area of convection creates a mesohigh (cold pool) that produces the increases in surface pressure (1–3 mb/24-hr) associated with a surge as it travels northward up the Gulf of California and into southern Arizona (Fig. 4).

Waves in the easterlies affect precipitation development in Arizona during the summertime owing to their more northward location. Easterly waves tend to develop at 700 mb between 10^{o}–25^{o} N, and are characterized by wavelengths of 2500 km, and periods of 3.5 days (Hastenrath 1991). Like Rossby waves, easterly waves tend to produce convergence just ahead of the trough axis (Reed 1977). The idea that easterly waves or other tropical disturbances are related to the development of surges over the Gulf of California is later corroborated by several authors (e.g., Stensrud et al. 1997; Anderson et al. 2000; Fuller and Stensrud et al. 2000). For instance, using analyses from a 32-day mesoscale model run, Stensrud et al. (1997) show that the strength of a surge is related to whether the passage of a midlatitude trough is in “the proper phase relationship” with a tropical easterly wave (Fig. 4; Stensrud et al. 1997). In the model, a stronger surge takes place when such a proper phase relationship occurs than when it is missing. Similarly, Anderson et al.’s (2000) analyses of 1990 and 1995 Southwest Area Monsoon Project (SWAMP) data indicate that surges of moisture from the Gulf of California, into Arizona, are initiated by either tropical cyclones or easterly waves, as they pass over the Gulf of California. Anderson et al. also show that, on average, surge events are associated with more widespread precipitation over Arizona than non-surge events. At the same time, analyses of a 14-yr data set by Fuller and Stensrud et al. (2000) show that within three days following the passage of a tropical easterly wave westward of 110^{o} W, 70% of such easterly wave passages were associated with a moisture surge at Yuma, Arizona.

The sporadic nature of these surges indicate that a more consistent process is responsible for the continuous southerly flow several authors find over the Gulf of California during the summertime (Rasmussen 1967; Houghton 1979; Tang and Reiter 1984; Badan-Dagon et al. 1991; Douglas et al. 1993; Schmitz and Mullen 1996; Higgins 1997). Using pilot balloon data collected during the 1990 SWAMP, Douglas (1995) shows that a nocturnal low-level jet (LLJ) develops below 700 mb over the northern part of the Gulf of California on a daily basis. Based on aircraft data, this LLJ is characterized by a 12 UTC speed maxima (~7 ms^{-1}) at a height of 500 m AGL over Yuma, and at a height of 250–400 m AGL over the Gulf of California. Using rawinsonde data collected at Tucson and Mazatlan, Douglas surmises that this low-level southerly flow is forced by a pressure gradient force that develops in response to a mean temperature difference (6^{o} C at 900 mb) between the stations. This mean temperature difference between Tucson and Mazatlan is similar to that calculated by Hales (10^{o} C,1974) for August 1972. Consequently, it appears that the pressure gradient force forces both the LLJ and surges, and that surges intensify this channelled flow.

In the late 1920’s, the collection of upper-air observations shift the attention of researchers from the thermal low to the newly observed mid–upper level anticyclone as a circulation important to the development of the summertime wet season over the southwest U.S. and western Mexico. Along these lines, Reed (1933; 1939) relates precipitation occurrence over Arizona to the position of a 500-mb closed anticyclone which develops in tandem with the thermal low. He suggests that precipitation is more likely to develop over Arizona when this high is located more eastward than westward of Arizona because air mass properties transported westward by the high may be more conducive to storm development (e.g., more moist air). Later, Bryson and Lowry (1955) produce a climatology of the southwest U.S. summertime mid–upper level anticyclone which examines both 700-mb and 500-mb flow. Like Reed (1933, 1939), their analyses identify a closed high at 500 mb. At 700 mb, the mean flow is a western extension of the Bermuda high, such that the flow moves easterly over the Gulf of Mexico, southeasterly over Mexico, and then southerly over Arizona (Fig. 5; Bryson and Lowry 1955). Based on this flow pattern, Bryson and Lowry surmise that moisture advected from the Gulf of Mexico into Arizona is the main moisture source for the summertime wet season; similar reasoning arose from Jurwitz (1953), although no analyses are shown in his paper.

The idea that the Gulf of Mexico is Arizona's major source of moisture during the summertime is later discounted by several authors who reason that air transported north-westward from the Gulf of Mexico into Mexico by the Bermuda High is dried substantially by the adiabatic lift and subsequent descent it experiences while passing over the Sierra Madre Oriental and the Sierra Occidental prior to reaching Arizona (Hales 1972a, 1974; Brenner 1974; Douglas et al. 1993). Furthermore, Douglas et al. (1993) point out that since the eastern slopes of Mexican mountain ranges are mostly dry during the summertime, and 700- and 500-mb air over the Gulf of Mexico is drier than that over western Mexico, such advective transport seems unlikely. Schmitz and Mullen (1996) attempt to answer this issue more thoroughly by analyzing ECMWF water vapor fields over Mexico and the United States. To discern differences in moisture transport between lower- and upper-levels, they calculate vertically integrated moisture flux vectors for the surface-to-700-mb layer and the 700-to-200-mb layer (Fig 7. of Schmitz and Mullen 1996). At low-levels such vectors point northward from the Gulf of California into Arizona, whereas at mid-levels such vectors point northwestward from western Mexico into Arizona. Schmitz and Mullen propose that such vectors support the idea that low-level moisture arises from the Gulf of California, and that mid–upper level moisture arises from the Gulf of Mexico. However, since these vectors essentially neglect mesoscale processes, it is possible that mid-level moist air over Arizona may originate, at least in part, from vertical mixing of moist air which moisten mid–levels over the mountains in western Mexico (Brenner 1974; Douglas et al. 1993). This air may then be advected over Arizona by the southeasterly-to-southerly flow of the mid-level anticyclonic flow.

While the NAM clearly corresponds with Arizona's wet season, periods of wet and dry weather occur during the NAM which coincide with variations in the mean synoptic environment (Carleton 1986; Watson et al. 1994a; Mullen et al. 1998). Mean synoptic environments associated with wet vs. dry periods are summarized below.

b. Mean synoptic environments associated with wet vs. dry periods during the NAM

During the NAM, Arizona experiences periods of wet and dry weather, called 'bursts' and 'breaks,' respectively. Such bursts and breaks have been analyzed using three different data sets, including: 1) 1980–1982 GOES-W infrared satellite data over the southwest *U.S.* (Carleton 1986), 2) 1985–1990 Bureau of Land Management lightning data over Arizona (Watson et al. 1994a), and 3) 1985–1992 precipitation data over southeastern Arizona (Mullen et al. 1998). In these studies, bursts and breaks are related to corresponding composite mid–upper level synoptic patterns to identify differences in synoptic regime responsible for periods of wet vs. dry weather. Interestingly, the 500-mb break composites created by these authors are essentially identical: an east-to-west oriented longwave ridge exists over the southwest U.S., whose ridge axis is located southward of central Arizona (Figs. 6a, 7a,c). In contrast, Carleton's 500-mb burst composite (Fig. 6b) differs significantly from those created by Watson et al. (Fig. 7b) and Mullen et al. (Fig. 7d). Carleton's 500-mb burst composite (Fig. 6b) shows a shortwave trough in the westerlies approaching the southwest U.S. from southeast Pacific, with the westward edge of the Bermuda High located over Texas, whereas Watson et al.'s (Fig. 7b) and Mullen et al.'s (Fig. 7d) 500-mb burst composite shows a longwave ridge dominating the U.S., with the horizontal ridge axis located northward of the Sonoran Desert. Note that Watson and Mullen's 500-mb break composites are similar to their 500-mb burst composites (Fig. 7b,d). While both of their burst and break composites show a longwave ridge over the western U.S., during breaks the flow is more zonal and the horizontal ridge axis is located farther southward. This southward shift in the horizontal ridge axis produces westerly flow over Arizona which, in turn, suppresses the advection of moisture into Arizona

Additionally, Watson et al. (1994a) and Mullen et al. (1998) show that tongues of moisture, extending from the Gulf of California, northward into Arizona, coincide with the burst composite only (Figs. 7b,d). This result supports the idea that surges from the Gulf of California are related to widespread precipitation occurrence over Arizona (Hales 1972a, 1974; Brenner 1974; Rowson and Colucci 1992; Stensrud et al. 1997; Anderson et al. 2000). Using European Centre for Medium-Range Weather Forecast (ECMWF) analyses, Mullen et al. (1998) corroborate previous analyses which suggested that low-level moisture transport from the northern Gulf of California into Arizona is a continous process during the summer season (Rasmussen 1967; Houghton 1979; Tang and Reiter 1984; Badan-Dagon et al. 1991; Douglas 1995; Schmitz and Mullen 1996; Higgins 1997). As expected, their analyses show that moisture is transported from the northern Gulf of California into southern Arizona during both bursts and breaks (Mullen et al. 1998). However, moisture transport from more southern parts of the Gulf during bursts is unclear. It is likely that the relatively large grid spacing of ECMWF analyses, coupled with a lack of surface observations over the Gulf of California and the eastern Pacific Ocean, are responsible for this apparent lack of moist transport from the Gulf of California into central Arizona. At mid–upper levels during bursts, more moisture is transported into southeastern Arizona from the Gulf of Mexico than during breaks, but the amount of moisture contributed by the Gulf of Mexico is small in comparison with the amount contributed by the Gulf of California (Mullen and Schmitz 1998).

The greater consistency within break composites vs. burst composites suggests that break composites may be more robust and lack sensitivities to domain, data type, or interseasonal variability, which may explain the differences between the burst composites. Such results reflect the challenges involved in assessing wet periods over Arizona when the synoptic pattern differs from the break composites. To address the apparent variability in synoptic regimes associated with wet periods over the southwest U.S., Carleton (1986) subjectively categorizes synoptic patterns associated with bursts and breaks. He finds that, during July and August 1980–1982, most bursts were associated with closed upper lows and upper long- or medium-wave troughs in the westerlies, located off the southern coast of California, whereas most breaks were associated with closed upper-level highs located over the Four Corners or east-to-west oriented long-wave ridge axes located south of the Sonoran Desert. Carleton’s finding that closed upper highs, located over the Four Corners, were associated mostly with breaks, implies that ridge axis location, by itself, is not a perfect indicator of a burst or a break. Rather, one needs to consider low-level moisture and lifting mechanisms as well (Carleton 1986). Below, mechanisms likely important to storm development in central Arizona are reviewed.

c. Mechanisms for storm development

Previous studies show that topographic features and interactions between topographic features and the atmospheric environment regulate storm development over elevated terrain (Banta 1990). Central Arizona contains a variety of terrain features which play a role in storm development; these features range in elevation from 42.6 m to 3915 m (Fig. 1). Diurnal climatology studies (Hales 1972b; Balling and Brazel 1987; King and Balling 1994; Watson et al. 1994b; MacKeen and Zhang 2000) reveal the tendency for storms to initiate first (near local noon) over the Mogollon Rim and White Mountains, followed by initiation over the Southeast Highlands. During the afternoon, storms move and/or redevelop southwestward down the central Arizona terrain gradient, and westward from the eastern terrain, culminating within the Sonoran Desert near sundown. This diurnal evolution is ubiquitous, appearing in climatologies using single radar data (Hales 1972b), precipitation gauges, (Balling and Brazel 1987), lightning data (King and Balling 1994; Watson et al. 1994b), and radar mosaic data (MacKeen and Zhang 2000). While early afternoon storms usually initiate over areas of higher terrain, spatial and temporal variability exists in initial storm locations and the evolution of such storms.

The investigation of spatial and temporal variability of storm development over higher terrain during Arizona's summertime wet season starts in 1959, when Ackerman (1959) studied echo locations and characteristics observed by a 3-cm wavelength radar near Tucson over a 7-day period. Soon afterward, studies begin to focus on how terrain and synoptic regime interactions relate to where storms initiate. For example, Fujita et al. (1962) completed a one-season mesoscale field study of precipitation over the San Francisco Mountains which shows that early-morning solar heating on the eastward facing slopes of the San Francisco Mountains initiates a mesolow, which, in turn, creates localized convergence and lift for convective storm development. Additionally, they find that higher rainfall amounts occur when 600-mb winds contain a southerly rather than a northerly wind component. Soon afterward, Orville (1965) completes a four-day study of storm initiation locations over the Santa Catalina Mountains near Tucson, which suggests that such storm initiation locations may be related to characteristics of 12 UTC Tucson soundings, such as wind direction and moisture profiles. Sensitivity of storm initiation location to synoptic regime is illustrated also by other extensive studies of cloud initiation locations over the Rocky Mountains in Colorado and New Mexico (Banta and Schaaf 1987; Schaff et al. 1988; Tucker and Crook 2001) and New Mexico only (Tucker 1993).

Although improved understanding of processes related to daily storm initiation locations is likely useful for improving probability of precipitation forecasts over higher terrain, a better understanding of processes conducive to storm redevelopment from the mountains surrounding the Sonoran Desert, into the Phoenix Metroplex, is also important. Since such storm evolution occurs relatively infrequently, it appears that atmospheric conditions differ significantly on days where storms redevelop off the mountains and into Phoenix, compared to days where storms develop over the mountains only. Since Phoenix became a new NWS rawinsonde site 1999, previous studies which attempt to relate local environmental conditions to convective storm development at Phoenix use either soundings collected during SWAMP or soundings collected at Tucson. Such studies overlooked the possibility of using soundings produced by a mesoscale model in place of the more sparse Phoenix soundings collected during SWAMP (Bright and Mullen 2001).

Hales (1977) begins the discussion of environmental conditions conducive to convective storm development in Phoenix by hypothesizing that tropospheric destabilization in Phoenix may sometimes be instigated by an advective process, where mid-level cloud-cooled air, produced by afternoon thunderstorms over the mountains, is advected over the relatively hot desert landscape. Later, using Phoenix soundings launched during SWAMP, Stensrud et al. (1993) show two cases where elevated residual layers (ERLs) are advected by a northerly wind from the Mogollon Rim to the 800–650 mb layer over Phoenix by early evening. An ERL is defined as a boundary layer, which may or may not be well-mixed, that forms initially over elevated terrain and is later advected over boundary layers developing over lower terrain (Stensrud et al. 1993). In both cases, rawinsondes launched three times between the late afternoon and early evening in Phoenix, show a warming and drying of the air between 800–650 mb, which decreases the convective potential substantially. The suppression of storm development over Phoenix owing to an ERL is emphasized by a case where storms fail to develop even though a convergence boundary, produced by thunderstorms moving off the mountains toward Phoenix, moves across Phoenix without producing new storm development. On this day, the associated ERL increased the Convective Inhibition (CIN) from an expected value of 87 J kg^{-1} to 264 J kg^{-1}, and decreased the Convective Available Potential Energy from an expected value of 800 J kg^{-1} to 594 J kg^{-1}.

Other case studies, such as McCollum et al. (1995), emphasize that subtle changes in Phoenix soundings and surface data are sometimes important. Specifically, during the 1990 SWAMP, both NWS and National Severe Storms Laboratory staff forecast incorrectly a dry evening over Phoenix on 23 July 1990—when instead a mesoscale convective system (MCS) developed. Later, detailed analyses of surface data, Phoenix soundings, and pibal wind reports from northern Mexico, suggested that mesoscale features, such as a southerly LLJ, dramatically improved low-level moisture and instability values. In combination with local convergence produced by thunderstorm outflow boundaries moving off mountains to the north, and opposing southerly flow south of Phoenix, such short-term changes made the Phoenix environment conducive to the development of a nocturnal MCS. In retrospect, close observation of environmental changes in the Phoenix soundings was crucial to nowcasting this event.

Since operational soundings are unavailable in the 1990s, several authors investigate also how well upper-air conditions at Tucson relate to weather conditions in Phoenix (McCollum 1993; Maddox et al. 1995; Wallace et al. 1999). To begin, McCollum et al. (1993) find three composite synoptic regimes associated with severe weather occurrence in Phoenix. Then, Maddox et al. (1995) investigate the relation of severe weather in Phoenix to both anomalous weather conditions over the U.S., computed from McCollum et al.'s three synoptic regimes, and upper-air conditions at Tucson. Without using statistical tests, Maddox et al. infer that such anomalous weather conditions over the U.S. relate to severe storm occurrence in Phoenix better than characterstics of Tucson soundings. Finally, Wallace et al. (1999) investigate differences in environmental conditions associated with storm days vs. no storms days in Phoenix by comparing associated surface conditions at Phoenix, and upper-air environmental conditions at Tucson. They find that storm days are slightly (1–2^{o}) more moist at the surface during the afternoon and evening than no storm days, and that on average, easterly wind speeds within Tucson's 700–450 hPa layer are slightly higher on storm days than on no storm days. Overall, such studies show Tucson soundings offer little utility for forecasting severe weather in Phoenix.

In summary, the circulations of the NAM provide an environment in Arizona conducive to summertime storm development. At low-levels, the temperature and pressure gradient between the southwest U.S. thermal low and the mesohigh over the mouth of the Gulf of California, constricted zonally by surrounding mountains, channels moist southerly flow in the form of a nocturnal LLJ—a flow intensified occasionally by the presence of tropical cyclones and easterly waves in the form of a surge. Since it is apparent that surges are related to storm occurrence over Arizona (Hales 1972a, 1974; Brenner 1974; Stensrud et al. 1997; Anderson et al. 2000; Fuller and Stensrud et al. 2000), a related topic pursued in this study is the relation of surges to the timing and location of storm development over Arizona. At mid–upper levels, the southeasterly-to-southerly flow over western Mexico and Arizona, respectively, helps moisten this layer via transport of water vapor. A related aspect of mid–upper level flow investigated in this study is the influence of this flow on where storms initiate and how the evolve.

While the NAM clearly corresponds with Arizona’s wet season, periods of wet and dry weather occur during the NAM which coincide with variations in the mean synoptic environment (Carleton 1986; Watson et al. 1994a; Mullen et al. 1998). Although such burst and break studies offer general guidelines for differentiating synoptic regimes associated with wet vs. dry periods during the NAM, the operational utility of such studies remains unverified. Specifically, burst and break studies provide little forecast guidance concerning where, when, and how storms may evolve on a given day. Several Arizona case studies point to the importance of interactions between mountainous terrain and mid-level wind direction (Fujita 1962), sounding characteristics (Orville 1965; Stensrud et al. 1993; Wallace et al. 1999), and convergence boundaries (McCollum et al. 1995) for producing conditions conducive to convective storm development. Consequently, this study examines the association of such environmental characteristics to mesoscale radar reflectivity patterns to improve the ability to forecast 1) where storms are likely to initiate over the elevated terrain within central Arizona, 2) how such storms are expected to evolve, and 3) whether storms are expected to develop in Phoenix. The next section describes the data sets used to address such forecast challenges.

3. Data

Three data sets are used to investigate the synoptic-scale and mesoscale processes related to storm initiation and evolution in central Arizona, including Weather Surveillance Radar-1988 Doppler (WSR-88D) radar reflectivity data, upper-air data, and Mesowest surface data. The NAM seasons analyzed in this study include July and August 1997, 1999, and 2001. Analyses span from July to August during each year because precipitation associated with the NAM usually begins in early July (Sellers and Hill 1974), and during September the NAM begins to dissipate. The analysis period begins in 1997 because it is the first year where radar data are available from both the Phoenix and Flagstaff WSR-88D sites. The 1998 and 2000 summer seasons are excluded due to large gaps in archived sounding data at Phoenix and WSR-88D data at Phoenix, respectively.

Radar reflectivity mosaics are used to investigate whether storms tend to initiate and evolve repeatedly over similar areas. These reflectivity mosaics are created from level II WSR-88D reflectivity data collected at the Phoenix (KIWA) and Flagstaff (KFSX) radar sites. Upper-air analyses (1200 UTC and 0000 UTC) produced by the Eta, and twice-daily rawinsonde data collected at Phoenix, are used to investigate how synoptic-scale conditions relate to where storms tend to initiate and how they evolve. Whereas previous studies of storm development in and around Phoenix rely on rawinsonde data collected at Tucson (Maddox et al. 1995; Wallace et al. 1999), this study offers a comprehensive examination of rawinsonde data collected at the new Phoenix rawinsonde site. These upper-air analyses are supplemented by rawinsonde data archived at Tucson, Yuma, and Guadalajara, which are used namely to help determine the occurrence of surges from the Gulf of California into Arizona. In addition, upper-air data archived at

Flagstaff are used to characterize the tropospheric environment over the complex terrain northward of Phoenix.

Mesowest data (Horel et al. 2001) are used to investigate the relation between the mesoscale environment in the Sonoran Desert and the development of storms in and around Phoenix. The MesoWest is a collection of surface observation stations located in the Intermountain West which are funded by independent agencies, private companies, and federal agencies (Horel et al. 2002). Mesowest data are quality controlled and objectively analyzed onto a 10-km spaced horizontal grid using the Oklahoma Advanced Regional Prediction System Data Analysis System (ADAS) and the RUC-2 as background (Horel et al. 2002).

4.0 Radar analysis

Previous studies of storm occurrence in Arizona tend to use precipitation or lightning data (e.g., Fujita 1962; Orville 1965; Balling and Brazel 1987; Watson et al. 1994b; King and Balling 1994) in place of single-radar data (Braham 1958; Ackerman 1959; Hales 1972) owing to radar limitations such as beam blockage, decreasing resolution with increasing range, and anomalous propagation. In this study, such radar data limitations are addressed by mosaicking, or mapping, radar reflectivity data from multiple radars that observe storms in central Arizona (Zhang 2000). Specifically, KIWA and KFSX reflectivity data are mosaicked to a common Cartesian grid to provide more complete depictions of storm structure and precipitation than either radar alone could provide.

Before the radar mosaic technique is applied, the radar reflectivity data are checked for ground clutter and anomalous propagation. In this quality control process, a radar reflectivity observation is considered ground clutter if the height of the observation is below the height of the corresponding terrain elevation. A radar reflectivity observation is considered anomalous propagation if its corresponding velocity magnitude is less than or equal to 2.5 ms^{-1} and the magnitude of the reflectivity value above the observation decreases quickly with height (Calvert 2001, personal communication 2001). Radar reflectivity data identified as ground clutter or anomalous propagation are removed from the data set. Once data quality control is completed, the mosaic technique (Zhang 2000) is applied to the quality controlled data.

The mosaic technique consists of three major steps (Zhang 2001, personal communication). First, polar-coordinate radar reflectivity data collected by the WSR-88Ds are mapped to a cylindrical equidistant latitude/longitude Cartesian reference frame. The Cartesian grid is 440 km x 440 km in the horizontal, and spans latitudinally from 32.04^{o} N to 36.43^{o} N, and longitudinally from -109.01^{o} W to 113.04^{o} W (Fig. 1). Grid resolution includes 1-km grid spacing in the horizontal, and 21 stretched levels in the vertical (surface to 12 km), such that height intervals increase hyperbolic-tangentially with increasing height.

Second, radar reflectivity values are interpolated to each grid point contained within an observed radar volume by performing an adaptive Barnes interpolation scheme:

$$f_g = \frac{\sum_{i}^{nbin} w_i \, f_o(i)}{\sum_{i=1}^{nbin} w_i}, \tag{1}$$

where $i = 1, 2, nbin,$ and the weight given to a radar observation is dependent on the distance between the grid point and the observation:

$$w_i = \exp\left[-\frac{(r_g - r_i)}{\kappa_r} - \frac{(\phi_g - \phi_i)}{\kappa_\phi} - \frac{(\theta_g - \theta_i)}{\kappa_\theta} \right]. \tag{2}$$

Here, f_g is the interpolated reflectivity at a given Cartesian grid point, f_o is the observed reflectivity at the i^{th} radar bin, w_i is the weight given to the i^{th} reflectivity observation, *nbin* is the number of radar bins influencing the interpolated grid value, r is data range, ϕ is azimuth, θ is elevation, and $\kappa = \kappa(r, \phi, \theta)$ are the filtering parameters. This Barnes interpolation is adaptive because the filtering parameters and size of the region influencing (hereafter called the “influence region”) the Cartesian grid value, f_g, are chosen to retain high resolution features in the radar observations. Since the resolution of radar reflectivity data decreases with increasing range from the radar, the region of influence used to interpolate radar reflectivity values to grid points located near the radar is smaller than the region of influence used to interpolate radar reflectivity values to grid points located far from the radar.

Third, once each volume scan of reflectivity from the KIWA and KFSX radars is interpolated to its associated Cartesion grid, the reflectivity values are mosaicked to each grid point (f_m) in the domain using an inverse distance-weighted average:

$$f_m(j) = \frac{\sum_{n=1}^{nradars} w_n(j)\, f_g^{\,n}(j)}{\sum_{n=1}^{nrad} w_n(j)}, \tag{3}$$

where *nrad* is the number of radars that cover the *jth* grid point (here *nrad* = 2), $f_g^{\,n}(j)$ is the *jth* interpolated reflectivity value from the *nth* radar, $f_m(j)$ is the mosaicked value at the *jth* grid point.

The weight given to a radar observation is dependent on the distance between the radar and the observation (i.e., Cressman weight function):

$$w_n(j) = \frac{R_{inf}^{2} - d_n^{2}(j)}{R_{inf}^{2} + d_n^{2}(j)}, \tag{4}$$

where R_{inf} is the farthest range at which a valid observation is attainable, and $d_n(j)$ is the distance between the j^{th} grid point and the n^{th} radar. The result of the mosaic technique is a 3-D radar reflectivity mosaic which is produced every 10 min. While such a 3-D data set may be used to examine storm structure characteristics, the main interest in this study is whether or not weather echos occurred within each grid box. Thus, to simplify processing, a 2-D mosaicked composite reflectivity product is used to discern weather from non-weather echo. The composite reflectivity product is a grid of the maximum reflectivity value within each 1-km x 1-km x 12-km column.

5. Radar reflectivity regimes and associated synoptic-scale conditions

Spatial variability in convective storm occurrence from the hourly composite reflectivity mosaics indicates four regimes. These reflectivity regimes are determined subjectively by observing the diurnal evolution of reflectivity mosaics for each day in July and August 1999. In these four reflectivity regimes, composite reflectivity evolves over the following areas in central Arizona: 1) eastern mountains (7 days or 11% of events), 2) central and eastern mountains (19 days or 31% of events), 3) central mountains, eastern mountains, and Phoenix (14 days or 23% of events), and 4) most of the domain (called widespread regime;17 days or 28% of events) (see Tables 1,2).

Characteristics of the evolution of these regimes, such as areas where radar reflectivity tends to develop repeatedly, are examined by calculating the relative frequency of composite reflectivity values greater than or equal to 25 dBZ over three three-hour periods, including: 18–20 UTC (early afternoon), 22–00 UTC (late afternoon), and 02 UTC–04 UTC (evening) (Figs. 8–11). A composite reflectivity threshold of 25 dBZ serves as a proxy for the convective storm development which predominates in central Arizona during the summertime. Figures 8–11 demonstrate that each reflectivity regime has a diurnal evolution that is punctuated by areas of repeated storm development over specific elevated terrain features. Such repeated storm development over elevated terrain illustrates the importance of terrain forcing in the initiation of moist convection in central Arizona during the summer season. Differences in the location of initial storm development among regimes suggest that differences in interactions between terrain and synoptic-scale conditions, such as the direction of the flow approaching the mountains, may be regulating where storms develop.

Below, significant features of each regime are discussed in light of associated synoptic-scale conditions. Synoptic-scale conditions are represented in three forms. The first form is a time-height cross section of the total wind and theta-e collected at 12 UTC in Phoenix from 14 July through 20 July (Fig. 12). This time period is chosen because all four regimes occurred during this week and it illustrates the most common evolution of such fields in central Arizona during July and August 1999. The second form is the 12 UTC 700-mb, and 500-mb synoptic-scale circulations associated with each day in the time-height cross section (Figs. 13–18). Finally, the third form is a group of box-and-whisker plots of 12 UTC sounding parameters at Phoenix, such as precipitable water and Convective Available Potential Energy (CAPE), which are used to characterize the range of such values associated with each regime (Figs. 19,20).

a. Widespread regime (WR)

The WR is characterized by days where storms occur over most of central Arizona (Fig. 8). In the WR, the diurnal evolution of relative frequency maxima suggest a tendency for storms to develop and move from west-to-east along the Central Mountains. Such is the case on 13 of the 17 WR days, likely owing to 1) the forcing and eastward movement of shortwave troughs as they approach Arizona, 2) the interaction of this southwesterly flow with the Central Mountains, and 3) deep tropospheric moisture. Such days are also associated with higher median total precipitable water (TPW) and CAPE values at Phoenix than other regimes (Fig. 19). The relation of approaching shortwave troughs to widespread storm development agrees with previous studies of burst events by Carleton (1986) and Watson et al. (1994a).

The evolution of synoptic-scale conditions associated with such a WR event is illustrated in Figs. 13–14. Fig. 13a shows that just prior to the 14–16 July event, at 700 mb, a northwest-to-southeast oriented axis of moist air exists over west-central Mexico and central and eastern Arizona. This deep tropospheric moisture is apparent in the associated time-height cross section of theta-e in Fig. 12. At 700 mb and 500 mb on the 14th (Figs. 13a, 14a), a closed longwave trough with embedded shortwave troughs in the westerlies is approaching Arizona from northwest. This system produces deep southwesterly tropospheric winds in the 12 UTC sounding at Phoenix (Fig. 12). The 700-mb and 500-mb westerly flow over Arizona at 12 UTC on 15 July (Figs. 13b, 14b; Fig. 12) indicates the passage of an embedded shortwave trough. A second embedded shortwave trough, located upstream of Arizona, passes over Arizona between 15 and 16 july which likely helps force this second and third day (15 and 16 July) of widespread storms over Arizona (Figs. 13b,c and 14b,c). By 12 UTC on 16 July, the packing of isodrysotherms over western Arizona at 700 mb indicates that the air at low- and mid-levels is beginning to dry in response to the advection of dry air from the deserts of southeastern California (Fig. 13c). Such drying of tropospheric air is indicated also by a decrease in theta-e at mid-to-upper levels in the associated 16 July Phoenix sounding (Fig. 12).

On the other four days where the widespread regime develops, a north-to-south oriented longwave ridge exists over the high plains whose ridge axis runs through eastern Wyoming, Colorado, and New Mexico (not shown), and nearly unidirectional southeasterly-to-easterly winds exist at Phoenix (not shown). Consequently, storms tend to move northwestward-to-westward, respectively. Analyses of 500-mb absolute vorticity indicate that relatively weak vorticity maxima tend to exist along or near the Gulf of California which may help force this widespread convection (not shown). Like widespread days associated with approaching shortwave troughs, widespread days associated with 500-mb high-amplitude longwave ridges are characterized by deep tropospheric moisture and plentiful CAPE (Fig. 19).

b. Eastern mountain regime (EMR)

The EMR is characterized by storm development over the mountains of eastern Arizona and relative frequency maxima of reflectivity which occur over the White Mountains and the Southeast Highlands (Fig. 9). Such days tend to occur following the passage of a longwave trough in the westerlies at 500 mb (e.g. 14–16 July). Consequently, associated Phoenix soundings are characterized by namely southwesterly-to-westerly winds with height (e.g., 17 July in Fig. 14), and relatively low total precipitable water and CAPE (Fig. 19).

The evolution of synoptic-scale conditions common to such a ER event is illustrated in Fig. 15. Notice that by 12 UTC on 17 July, westerly flow at 700 mb has advected dry air from the southwest deserts across most of Arizona, such that the 700-mb dewpoint gradient located across western Arizona at 12 UTC on 16 July (Fig. 13c), is now located in western New Mexico (Fig. 15a), and relatively moist air is limited to southeastern Arizona. The presence of drier air in central Arizona is indicated also by the relative minima in theta-e between low-to-upper levels at Phoenix (Fig. 12). The 500-mb synoptic-scale flow associated with such days is usually southwesterly, and in this case, is associated with a low-pressure system in the westerlies located over western Washington and Oregon (Fig. 15b). Storm development is likely preferred over the White Mountains and Southeast Highlands during ER events owing to the presence of low-level moisture over southeastern Arizona only, conditionally unstable lapse rates, and terrain forcing.

c. Central, eastern, and Phoenix regime (CEPR)

The CEPR is characterized by the development of convective storms over the Mogollon Rim and Southeast Highlands during the early afternoon, the movement and redevelopment of storms from higher terrain toward the lower terrain of the Sonoran Desert during the late afternoon, and the movement and redevelopment of storms into the Sonoran Desert and Phoenix during the evening (Fig. 10). This regime is similar to the evolution of storms depicted by studies of Arizona's diurnal climatology (Balling and Brazel 1987; King and Balling 1994; Watson et al. 1994b). Such days are often associated with easterly flow between 700 mb and 500 mb over Arizona, and moderate-to-high precipitable water and CAPE values at Phoenix (Fig. 19). This mid-level easterly flow is usually associated with closed high pressure center located over the Four Corners. The case shown here, 18 July 1999, is especially interesting owing to the quick return of low-to-mid-level moisture (Figs. 12, 16a) following the widespread drying across Arizona the previous day (Figs. 12, 15a). It appears that this rapid change in low-level moisture and tropospheric wind direction is associated with a 700-mb low which exists over northwest

Mexico at 12 UTC on 18 July (Fig. 16a). The role this disturbance may have played in this CEPR event will be investigated further in future work.

d. Central and eastern mountain regime (CEMR)

The CEMR is characterized by days where storms form mostly over the Mogollon Rim (Fig. 11). Unlike the EMR, relative frequency maxima exist along the northwestern part of the Mogollon Rim (e.g. San Francisco Mountains) rather than along the southeastern part of the Mogollon Rim (e.g. White Mountains, Fig. 9). In addition, storm development over the Southeast Highlands dominates later in the afternoon on CEMR days than on EMR days. Such differences in where storms tend to develop first, and how they evolve, are likely related to the low-level moisture content at Phoenix (e.g., 19 and 20 July in Figs. 12, 17a,b) and terrain elevation. In general, CEMR events are associated with relatively high total precipitable water and CAPE compared to ER events (Figs. 19, 20). The evolution of synoptic-scale conditions common to such a CEMR event is illustrated in Figs. 17 and 18. Notice that by 19 July, a deeper layer of moist air exists at Phoenix than on 17 July, but the wind profile is similar, with southwesterly-to-westerly tropospheric winds with height (e.g., 19 and 20 July in Fig. 12) owing to an 500-mb closed low in the westerlies approaching Arizona from off the coast of southern California (Figs. 17, 18). Thus, when ample low-level moisture and CAPE exist in central Arizona, it is likely that southwesterly-to-westerly winds help provide the terrain-forced convection that tends to form first over the higher elevations owing to their earlier response to solar heating than lower elevations. In addition, it is possible that the southwesterly-to-westerly steering level winds (700–500 mb) on such days tend to mitigate the movement of storms from higher to lower elevations, such that convergence boundaries from mountain-produced storms are unable to advance into the Sonoran Desert.

6. Summary and future work

Analyses of WSR-88D reflectivity data from July and August 1999 show that terrain forcing is an important component of summertime storm development in central Arizona. During this season, four radar reflectivity regimes are identified: 1) eastern, 2) central and eastern, 3) central, eastern and Phoenix, and 4) widespread. The repitition of convective storm development over such specific regions suggests that where storms initiate, and how they evolve, is related, at least in part, to synoptic-scale conditions. Although some characteristics of the 12 UTC Phoenix sounding, such as total precipitable water and CAPE, are not exclusively unique to each regime, the coupling of such characteristics with the 700–500 mb wind at Phoenix, the low-level moisture, and the synoptic-scale patterns at 700 mb and 500 mb, appear potentially useful for assessing the predominate storm regime for a given day. The two dominate regimes in 1999 included the WR (19 days or 31% of events) and the CER (17 days or 27% of events), which were driven by different forcing mechanisms: the WR was driven primarily by the synoptic-scale forcing associated with longwave troughs with embedded shortwave troughs in the westerlies, whereas the CER was driven primarily by terrain forcing. Like the CER, the CEPR (14 days or 23%) and ER (7 days or 11%) were driven namely by terrain forcing, but the CEPR was unique in that secondary storm development, occurred from higher toward lower terrain into Phoenix. It is likely that the relatively high values of precipitable water and CAPE in Phoenix, coupled with easterly steering-level winds, are important to the occurrence of this regime. In addition, the association of each terrain-driven regime with relatively unique relative frequency maxima over specific terrain features during the early afternoon, suggests that attention to such spatial reflectivity patterns may serve as a nowcasting tool for the short-term spatial development of convective storms.

While analyses of 1999 reflectivity and synoptic-scale data demonstrate the potential for improved forecasts of storm initiation and evolution over central Arizona, some important aspects of this study require further attention. For one, the relation of mesoscale surface data and supplemental soundings to storm initiation and evolution in central Arizona still need to be examined. It is hypothesized that gradients in mesoscale fields, such as surface moisture and/or temperature in and around Phoenix, are related to whether storms form in that area. It is also hypothesized that the sudden returns of moisture, apparent in the theta-e time-height cross sections at Phoenix, and the horizontal dewpoint temperature distributions at 850 mb, are related to surges of moisture from the Gulf of California similar to those described by Hales (1972, 1974), Brenner (1974), Stensrud (1997), and Anderson (2001). Such surges will be defined using surface data in southern Arizona, combined with upper-air data from Yuma, Tucson, and Guadalajara on the occasions where these data are available. Based on 1999 results, it is hypothesized that once low-level moisture is in place over central Arizona, the occurrence of the CER vs. the CEPR is tied strongly to the direction of the steering-level winds over Arizona.

To address the above hypotheses in a more thorough manner, the analysis methodology applied in this study will be extended to similar data sets collected in 1997 and 2001. Assuming that relatively similar results are found, composite Phoenix soundings, synoptic-scale analyses, and mesoscale analyses will be created for each reflectivity regime, and the variability in such observed conditions assessed. It is hypothesized that such composite conditions explain enough of the variance in reflectivity associated with each regime, that a properly designed version of the MM5, initialized by each composite, will be able to reproduce the relative frequency characteristics of radar reflectivity associated with each observed regime. The MM5 is chosen owing to the ability of a previous version of the model (version 4 or MM4) to reproduce many of the observed features of the NAM (Stensrud et al. 1995) over Mexico, such as the large-scale mid-level wind field and southerly low-level flow over the Gulf of California. In addition, the MM4 was able to simulate observed moisture surges and heavy rainfall events over western Mexico. The exact configuration of the model runs is yet to be determined.

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